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Transport of dust particles in tokamak devices*

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Abstract

Recent advances in the dust transport modeling in tokamak devices are discussed. Topics include: (1) physical model for dust transport; (2) modeling results on dynamics of dust particles in plasma; (3) conditions necessary for particle growth in plasma; (4) dust spreading over the tokamak; (5) density profiles for dust particles and impurity atoms associated with dust ablation in tokamak plasma; and (6) roles of dust in material/tritium migration.

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1. Introduction

Dust has been identified as having a potentially large impact on fusion-scale plasma experiments [1-3]. Understanding and predicting the role of dust require models of the mechanisms of production, plasma and surface interactions, and transport within and outside the plasma. Furthermore, one must understand dust removal, as well as assessing dust impact on core plasma performance, tritium retention and in-vessel inventory, and the safety of next-step fusion devices. Indeed, dust safety limits and control are important parts of the ITER R&D program [1,2], including the development and validation of simulation capabilities. In the paper, we discuss modeling of dust transport in tokamaks, analyze the conditions leading to dust growth in plasma, study the penetrability of dust particles originating from the tokamak chamber through vacuum ducts, and present the results obtained with DUSTT and UEDGE codes on dust transport, dust particle density, and density of impurities originated from dust ablation.

2. The DUSTT code

A physical model [3,4] for dust transport in fusion devices includes the dynamics of dust-plasma, dust-turbulence, and dust-surface interactions. The dynamics is strongly coupled to heating, charging, erosion, evaporation, and thermo-chemical properties of dust particles. These processes have been incorporated into the DUST Transport (DUSTT) code [4] that includes the following capabilities: a 2D curvilinear non-uniform mesh based on MHD equilibrium; multi-species plasma and neutral-gas parameters calculated by the edge plasma/neutrals transport code UEDGE; and tracking of test dust particles in 3D using the resulting force (\mathbf{F}_{tot} , the vector sum of Lorentz, ion and neutral friction, and gravity forces), particle and energy fluxes, and other parameters based on UEDGE data. DUSTT employs a

Monte Carlo method to simulate collisions and to perform averaging over an ensemble of test dust particles.

In modeling, we assume that the dust particle is spherical with radius R_d and has uniform temperature T_d . It is comprised of uniform solid matter with atom density ρ_d , mass m_d , heat capacity $C_d(T_d)$; so dust mass is $M_d = 4\pi R_d^3 \rho_d / 3$. The DUSTT code solves the equations of dust particle motion: $d\mathbf{r}/dt = \mathbf{v}$, $d\mathbf{v}/dt = \mathbf{F}_{\text{tot}}/M_d + \mathbf{G}_{\text{col}}$, together with the equations for temporal evolution of R_d and T_d : $\rho_d dR_d/dt = m_d(\Gamma_{\text{in}} - \Gamma_{\text{out}})$, and $d[C_d M_d T_d]/dt = 4\pi R_d^2 (q_{\text{in}} - q_{\text{out}})$. Here operator G_{col} describes collisions with walls, the incident flux Γ_{in} is multi-species, the flux Γ_{out} emanating from the dust is due to reflection (Γ_{bse}) of incident particles, physical (Γ_{phs}) and chemical (Γ_{chs}) sputtering, radiation enhanced (Γ_{res}) and thermal (Γ_{sub}) sublimations. Incident heat q_{in} is due to ion and electron kinetic energy transfer, plasma radiation, and potential energy release, whereas the heat flux $q_{\text{out}} = q_{\text{bse}} + q_{\text{rad}} + q_{\text{kb}}$ from dust is via reflection, thermal radiation, and kinetic and binding energy of ejected particles. We use a non-black-body expression $q_{\text{rad}}(T_d, R_d)$ generalized for arbitrary small R_d . The surface potential χ is calculated by equilibrating the ion and electron fluxes at the surface: $J_e - J_{\text{see}} - J_{\text{the}} = J_i$, where J_e and J_i are the fluxes from plasma, J_{see} and J_{the} are the secondary electron and thermal electron emission fluxes. We use generalized expressions for J_{see} and J_{the} that incorporate the space charge effects. The incident fluxes: Γ_{in} , q_{in} , J_e, J_i , are calculated based on the OML theory. DUSTT handles the generalized case when ions and neutrals are multi-species and are in different charge states as simulated with UEDGE.

The results on dust particle dynamics are shown in Fig. 1. The calculations of two sample trajectories and corresponding evolution of dust parameters ($L_p = \int [v_r^2 + v_z^2]^{1/2} dt$) are done with DUSTT/UEdge for 1- μm carbon particles launched at outer divertor plate in an L-mode shot [4] on DIII-D tokamak. As seen, these dust particles are very mobile and accelerate to large velocities due to ion friction force (average speed is 400m/s). In hot plasma regions

the particles heat up to sublimation temperatures and hence efficiently lost their mass. In such regions the dust charge becomes positive due to secondary and thermal electron emissions, however, the positive charge is small because of space charge buildup. Relatively deep penetration of dust particles toward the plasma core is predicted.

3. Conditions for dust growth in plasma

Under standard plasma discharge conditions, dust particles in plasma experience the net erosion or sublimation. However, in some cases (for example, detached plasmas in divertor and private flux regions or parasitic plasmas that occur underneath a dome in some tokamaks), the dust particles can grow from net deposition when a low-temperature, low-density plasma contains significant concentrations of intrinsic impurities.

To highlight the conditions necessary for dust growth, we use the simple model suggesting that carbon-dust particle is embedded in stationary plasma (n_e, T_e) and neutral gas (n_a, T_a). The deuterium plasma contains a fixed fraction γ_c of singly charge carbon ions ($[C^+] = \gamma_c n_e$) and neutrals ($[C^0] = \gamma_c n_a$). Input parameters are n_e, T_e , and γ_c . We assume $[D^+] + [C^+] = n_e$, $n_a = \eta_{\text{gas}} n_e$, $\eta_{\text{gas}} = 1$, $T_e = T_i$, $T_a = \eta_{\text{ai}} T_i$, $\eta_{\text{ai}} = 0.3$, and iteratively solve a set of transcendental equations involving: (1) plasma particle fluxes J_e, J_i , (2) equilibrium potential χ from $J_e - J_{\text{see}} - J_{\text{the}} = J_i$, (3) incident heat flux $q_{\text{in}}(\chi)$ and emanating radiation $q_{\text{rad}}(T_d, R_d)$, (4) equilibrium dust temperature $T_{d,\text{eq}}$ from the balance $q_{\text{in}} = q_{\text{out}}$, (5) deposition Γ_{in} and erosion Γ_{out} rates, and (6) effective erosion/deposition rate dR_d/dt from the imbalance $m_d(\Gamma_{\text{in}} - \Gamma_{\text{out}})/\rho_d$. The results of our calculations are shown in Fig. 2. The sputtering and sublimation yields depend strongly on $T_{d,\text{eq}}$. The dust temperatures in the range $700 < T_{d,\text{eq}} < 1800\text{C}$ are favorable for deposition since chemical sputtering is suppressed while sublimation yields remain small. For $1\text{-}\mu\text{m}$ dust and $5 < T_e < 20\text{ eV}$, such $T_{d,\text{eq}}$ are attained when $0.5 < n_e/(10^{12}\text{cm}^{-3}) < 5$. In this range of $T_{d,\text{eq}}$ and n_e , as seen in Fig. 1, even small concentrations of impurities ($\gamma_c \sim 1\%$) result in the net

deposition. For $T_e=10\text{eV}$, $n_e=10^{12}\text{cm}^{-3}$, $\gamma_c=1\%$, we obtain $T_{d,eq}\approx 1100\text{C}$ and dust growth rate is $\approx 10\text{ nm/s}$. In impurity rich (several %) plasmas, dR_d/dt can be around $+100\text{ nm/s}$.

4. Modeling of dust spreading in a tokamak

Spreading of dust throughout the device is an important safety issue, since larger amounts of dust can be mobilized in an accident. It is expected that dusts produced in the working chamber will penetrate far into the pumping ducts, NBI and diagnostics ports, antennae, etc. We use Monte Carlo method to evaluate the penetrability of dust particles into the rectangular ducts. We consider both horizontal and vertical (gravity directed toward the exit) ducts with dimensions $d \times d \times L$, where d and L are the width and length. We assume that incident particles have uniform distribution over the area of duct opening and over the azimuth angle and cosine of polar angle. The initial velocity v_{d0} and radius R_{d0} are input parameters. Collisions with walls are described by diffusive and mirror reflections (equal probabilities are taken here). In each collision the particle sticks to the surface with probability $1-\gamma_m$, whereas velocity of reflected particles reduces by the factor γ_v . The real values of γ_v and γ_m are unknown. Then, we scan the γ_v and γ_m values and compute the fluxes of dust particles that stick to walls (Φ_{wal}) and leave the duct through the entrance (Φ_{rfl}) and exit (Φ_{out}) openings (the flux balance demands $\Phi_{rfl}+\Phi_{out}+\Phi_{wal}=\Phi_{in}$). The results are shown on Fig.3 for $d=0.1\text{m}$, $L=1\text{m}$. As seen, the Φ -fluxes depend strongly on gravity, in particular, when initial velocity is small or momentum losses in wall collisions are strong. Vertical duct efficiently collects slow dust particles. The profiles of dust flux Φ penetrating into horizontal ducts are shown on Fig.4. As seen (bottom), for strong sticking $\gamma_m \leq 0.5$, the penetrating flux is dominated by particles experiencing no collisions so that the dependence of Φ on γ_v is small. For high reflection probability $\gamma_m=0.95$ (top), the highest penetration is when $\gamma_v \sim 1$. In this

case, dust particles are similar to atomic particles and, asymptotically, $\Phi/\Phi_{\text{in}} \propto d/L$. Momentum losses reduce the penetration, e.g., due to gravity effects.

From UEDGE modeling of typical LSN L-mode shot in NSTX we obtain the total impurity source due to sputtering is $\approx 10^{23}/\text{s}$. Assuming that 1% of this amount is converted into 1- μm dusts and using DUSTT, we evaluate the average flux of carbon carried by dust particles to the outer wall as $\Phi_{\text{in}} \approx 10^{12} \text{ atom}/\text{cm}^2/\text{s}$. For $\gamma_v = \gamma_m = 0.5$ the flux passing through the duct with $d/L = 0.1$ is $\Phi_{\text{out}}/\Phi_{\text{in}} \approx 0.01$ (Fig. 4). During experimental campaign $\tau_c \approx 100 \text{ days} \times 50 \text{ shots} \times 4 \text{ seconds}$, this flux is capable of generating a deposited layer of significant width $m_d \gamma_m \Phi_{\text{out}} \tau_c / \rho_d \approx 2 \text{ nm}$.

5. Dust profiles in tokamak plasma

We use DUSTT to calculate statistically averaged profiles of dust parameters in the tokamak plasma. Since dust generation rate and source profile are unknown, we use simplified model suggesting that (i) dust production rate is a fixed fraction ξ of total carbon erosion Ξ_{spt} by plasma, (ii) dust source profile is akin to carbon deposition profile; and (iii) angular distribution of particles is isotropic in 2π , whereas initial velocity modules is fixed. The calculations here are done under assumption that all test particles born with the same radius $R_{d0} = 1 \mu\text{m}$ and their flux is $\Gamma_d = m_d \xi \Xi_{\text{spt}} / M_d$. We use the plasma background and erosion/deposition profiles calculated with UEDGE for L-mode shot in NSTX. We launched large number ($\sim 10^5$) of test dust particles to attain satisfactory accuracy. We also assign the statistical weights to particles and employ various techniques for statistical variance reduction, e.g. suppression of dust absorption and systematic sampling of particles from sources. The calculated profile of dust particle density (all radii) is shown in Fig. 5. The dust density is peaked near the divertor plates which are the dominant dust sources. The particles quickly accelerated by plasma flow in the recycling region and spread over the divertor volumes. Due

to evaporation, dust density decreases closer to the core. Above mid-plane the density originates predominantly from chamber wall sputtering. With DUSTT, we also calculate the source of carbon atoms due to dust ablation, and then, ablation source is inputted into UEDGE to compute the corresponding profile of neutral carbon density. The profile of carbon atoms originated from dust ablation at conversion efficiency $\xi=1\%$ is shown on Fig. 5. It is compared to the atomic carbon density profile corresponding to the usual sputtering source. As seen, while sputtered atoms are strongly localized near material surfaces, the ablation of dust maintains relatively large impurity neutral density in the SOL and substantially enhances the impurity atom concentration in the core.

The role of dust in the impurity source advancement deep into the plasma and in the core plasma contamination is illustrated on Fig.6. Here we compare the radial profiles of carbon atom at 7 cm below the outer mid-plane, which originate from usual sputtering source and from dust ablation sources with $\xi=100$, 1, and 0.01%. As seen, neutral carbon density at the separatrix ($\rho=0$) from dust ablation is comparable to that from sputtering at very low deposit-to-dust conversion efficiency: $\xi\approx 0.01\%$. In the case of $\xi=100\%$, the carbon neutral density is even comparable to the density of deuterium neutrals around the separatrix.

6. Discussion

Based on carbon dust transport simulations with DUSTT and UEDGE codes, we have showed that: (1) dust particles can grow at the rate 10-100 nm/s from net deposition in the tokamak edge (isolated regions with $T_e=10$ eV, $n_e=10^{12}\text{cm}^{-3}$ $[C^+]/n_e>1\%$ plasma); (2) if momentum loss in dust-wall collisions is small, dust particles penetrate deep into vacuum ducts, and thus, spread the hazards over a large area; (3) penetration of dust toward the core plasma represents a significantly enhanced impurity source there.

As follows from our UEDGE simulations, a feedback can occur where radiation from ionized dust-impurities can reduce the divertor temperature, which in turn allows further penetration of the dust and associated impurities. Such a feedback can result in strongly detached inner divertor-leg plasma.

In LSN configuration, the impurities sputtered from the outboard wall are entertained in the SOL by parallel plasma flows into the inner divertor and are deposited on the plate. Experiments showed that the inner plate (IP) exhibits net deposition. According to UEDGE modeling, the amount of material carried by plasma flow (about several amperes in L-mode shots) is approximately equal to net deposition rate. Along with impurities, the IP is expected to retain more working gas (tritium in ITER). At the same time, dust particles originating from IP preferentially move outboard due to centrifugal force resulting from dust acceleration by toroidal plasma flows. Hence, dust can potentially connect the material migration in a loop. To study material migration loop, we intend to perform fully self-consistent modeling of plasma, impurities, and dust transport with coupled DUSTT and UEDGE codes.

References

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Figure captions:

Fig.1: Traces of 3D trajectories on UEDGE mesh for two dust particles in DIII-D discharge (upper left). Other panels display the evolution of dust parameters with the length L_p .

Fig.2: Net (upper two panels) and partial (bottom) erosion/deposition rates dR_d/dt and equilibrium temperature $T_{d,eq}$ of 1- μm dust are displayed as functions of plasma density.

Fig.3: Dust particle fluxes reflected from (Φ_{refl}) and passing through (Φ_{out}) the horizontal and vertical ducts versus factor γv for velocity reduction in collisions.

Fig.4: Normalized flux of dust particles versus distance into the horizontal duct.

Fig.5: Profile of dust particle density (left) calculated with DUSTT/UEDGE for NSTX. Profiles of carbon atom densities associated with usual plasma sputtering source (middle) and with 1%-deposition 1- μm dust ablation source (right).

Fig.6: Radial profiles of carbon atom density near the outer mid-plane in NSTX. The profiles are associated with sputtering impurities (solid line) and with dust ablation sources of different intensity (broken lines).

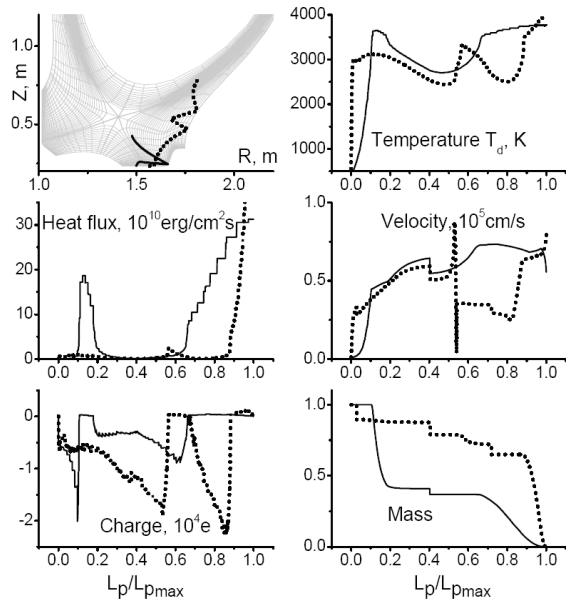


Fig. 1

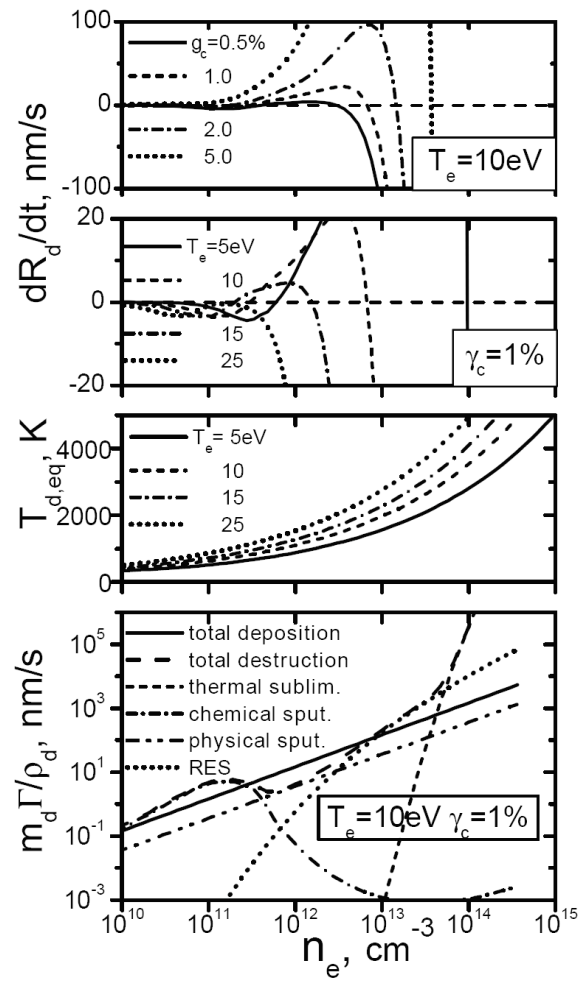


Fig. 2

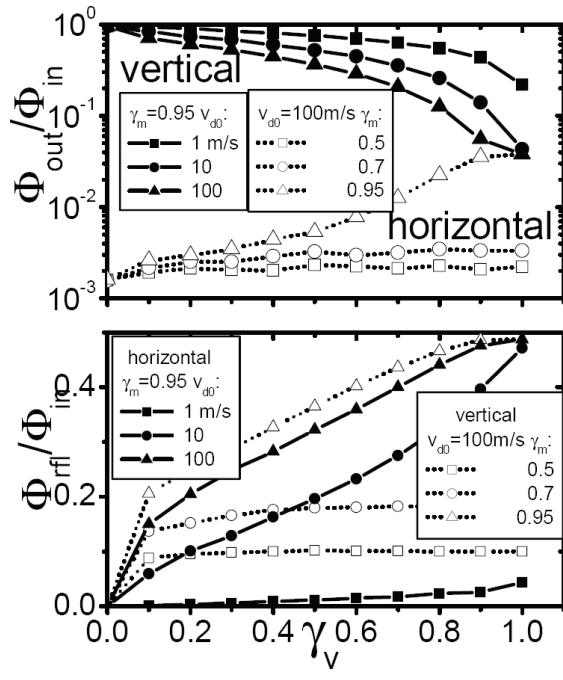


Fig. 3

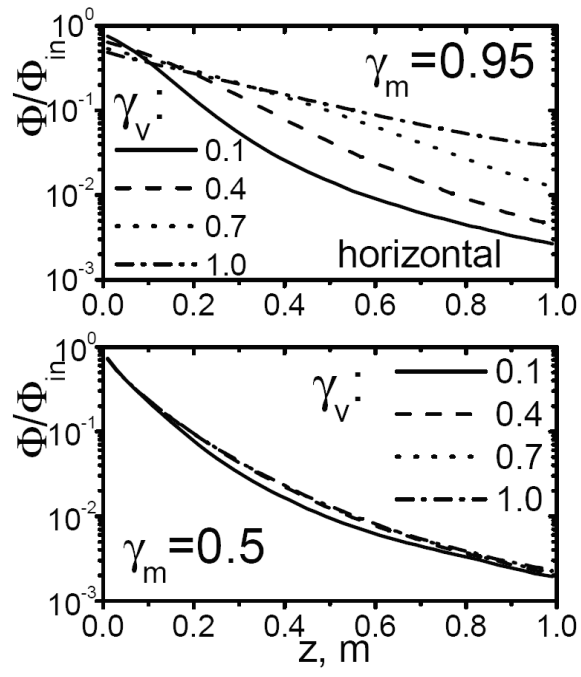


Fig.4

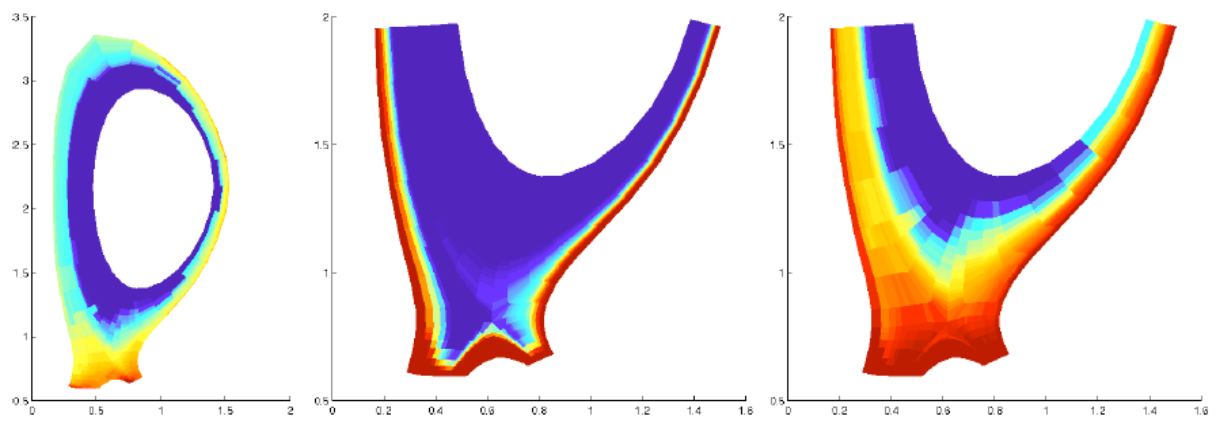


Fig.5

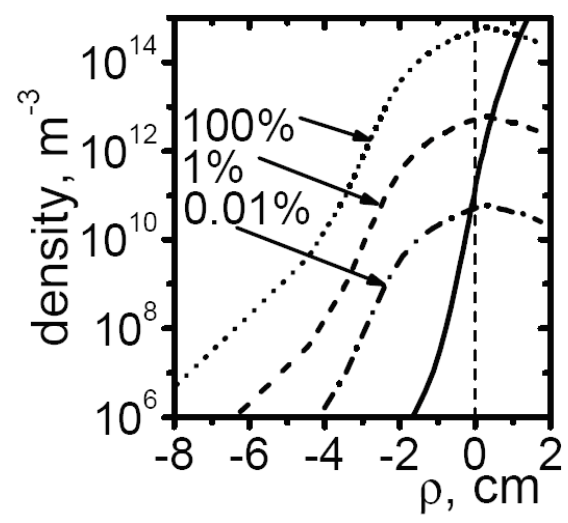


Fig.6